Abstract—This paper introduces SpaceBok, a quadrupedal robot created to investigate dynamic legged locomotion for the exploration of low-gravity celestial bodies. With a hip height of 500 mm and a mass of 20 kg, its dimensions are comparable to a medium-sized dog. The robot’s leg configuration is based on an optimized parallel motion mechanism that allows the integration of parallel elastic elements to store and release energy for powerful jumping maneuvers. High-torque brushless motors in combination with customized single-stage planetary gear transmissions enable force control at the foot contact points based on motor currents. We present successful walking, trotting, and pronking experiments. Thereby, Spacebok achieved maximal jump heights in single jump experiments of up to 1.05 m (more than twice the hip height) and a walking velocity of 1 m/s. Moreover, simulation results for low gravity on the moon suggest that our robot can move with up to 1.1 m/s at an approximate cost of transport of 1 in moon gravity when using the pronking gait.

I. INTRODUCTION

Until now, solely wheeled locomotion has been used for mobile exploration of celestial bodies. Rovers have been constantly improved, but never replaced by fundamentally different systems due to their reliability and low complexity. However, the applicability of wheeled systems in unstructured and steep terrain is limited, which prevents them from exploring scientifically interesting areas like craters [1].

To overcome these limitations, legged robots provide a very promising alternative for space exploration. In this context, several prototypes of legged or hybrid wheeled-legged systems have been developed, such as Scorpion [2], SpaceClimber [3], or ATHLETE [4]. These systems can walk robustly on uneven ground by using static gaits, whereby a minimum of three feet in ground contact ensure a statically stable stance at all times. However, these systems cannot perform dynamic maneuvers, which limits the traversal speed, agility, and operational reach of the robot [2], [3], [4].

Several dynamically balancing legged robots have been developed for terrestrial applications in recent years, such as ANYmal [5], MIT Cheetah [6], HyQ [7], Minitaur [8], Spot Mini [9] or Salto [10]. These systems make use of dynamic gaits to locomote efficiently and robustly at high speeds on a variety of surfaces. These robots can change the gait as a function of the terrain and the desired speed, thus reaching a high level of mobility and agility. Additionally, it has been shown in simulation that highly dynamic gaits with extended flight phases during the gait cycle allow efficient locomotion in low gravity at high velocities [11]. While Salto can perform gaits with long flight phases, its mechanical design is not suitable to transport payloads of at least 1.5 kg as needed for common instruments in space exploration [1]. Minitaur exhibits a broad variety of gaits and shows impressive capabilities. However, the direct drive that allows precise proprioceptive force sensing through actuator currents also has drawbacks. With the use of geared drivetrains, medium-size class robots can be operated with the same motors. Additionally, Minitaur has no elastic elements to store energy and provide more efficient locomotion.

Motivated by these findings, we developed the quadrupedal robot Spacebok (Fig. 1) which is specifically built for dynamic locomotion in low gravity with a focus on a highly dynamic pronking gait. With this gait, where the robot jumps with all four legs at once, extended flight phases are possible. The purpose of SpaceBok is to serve as a platform for locomotion studies. To be able to test the robot on Earth, we considered loads that occur in Earth gravity for the design. The system is designed lightweight, with low leg inertia and powerful actuation aligned at the hip axis, which allows powerful jumping maneuvers. The mechanism allows the integration of parallel springs that can improve jumping height and increase locomotion efficiency. With increased jump heights, it becomes easier to overcome obstacles in a rough environment.

Section I describes the system design of the robot with a focus on leg kinematics and actuator design. Section III discusses the implemented controller. In section IV experimental and simulation results are presented. Section V provides a conclusion and an outlook on future application and improvement of the robot.
II. SYSTEM DESIGN

SpaceBok is a quadrupedal robot with two actuated degrees of freedom (DOF) per leg (Hip flexion/extension, Knee flexion/extension). Abduction/adduction was omitted to reduce the weight of the system. We developed custom actuators consisting of brushless DC motors in combination with integrated custom planetary gearboxes to provide high torque and power at a small form and weight factor. The legs are mounted onto a lightweight and rigid carbon monocoque. The carbon body protects the electrical system, which is tightly packed into a single, removable stack. The robot has a mass of 20 kg and a hip height of 500 mm. We laid a focus on the leg geometry. The leg inertia was kept as low as possible to enable fast and efficient leg motion.

A. Leg Design

Several existing systems such as ANYmal [5] use a serial linkage with an actuated hip- and an actuated knee joint. This design provides a big range of motion of the leg. However, leg inertia is high due to the placement of the knee actuator. The leg inertia can be reduced by placing the motor at the hip joint as in other robots such as MIT Cheetah3 or Minitaur. We used a parallel motion design (Fig. 2), similar to the one of Minitaur [8]. We optimized the design for high jumps. The parallel motion linkage allows concentrating the actuator mass in the hip, thus reducing leg inertia. Furthermore, both actuators are equally contributing during the acceleration phase of a jump.

We optimized the segment lengths $l_1$ and $l_2$ for maximum jump height under the constraint that it is possible to integrate tension springs (Fig. 2). In the shown mechanism, this leads to a link length ratio of $\frac{l_1}{l_2} \approx 2.1$. The link lengths $l_1 = 250 \text{ mm}$ and $l_2 = 120 \text{ mm}$ were chosen. We evaluated the resulting jump height in a dynamic MATLAB Simscape simulation of a single leg, constrained to a one-dimensional vertical motion. The single leg system reached the desired jump height of 400 mm ground clearance with stretched legs in this configuration. To minimize leg mass and inertia, commercially available carbon tubes were used for the links.

B. Actuator design

Most existing legged robots are actuated by direct drives [12], drives with series elastic elements [5], or pseudo-direct drives [6], where a high torque motor is combined with a low-reduction gearbox. In other systems, hydraulic actuators are used [7], which are not feasible for space applications. For the actuation of SpaceBok, we chose off-the-shelf brushless DC-motors (T-Motor U8 KV85) in combination with custom-designed single-stage planetary gearboxes. In our design, the planetary gearbox is placed within the stator frame, which reduces hip width. We chose a high transmission ratio of 9.55, which leads to a maximum output torque of 39.5 Nm when the motor is operated at 30 A. An off-the-shelf absolute magnetic rotary encoder (RLS AksIM-2) is placed off-axis. The motors are driven by ELMO Twitter Gold motor controllers, which are placed within the main body on a specially designed cooling channel (Sec. II-C). This pseudo-direct drive design allows an accurate estimate of the torque at the output shaft based on current measurements, which makes additional force/torque sensors obsolete. A high output torque can be generated, and the whole drivetrain remains back-drivable. In combination with the bearing concept illustrated in Fig. 3, the actuation system can cope with the potentially high impact loads occurring during landing. The whole drive is compact and lightweight with a weight of 620 g per DOF, which includes the motor, gearbox, aluminum frame, and bearings.

C. Electrical system integration

To enable clean cable management and facilitate maintenance all electrical components are mounted on a single, removable stack (Fig. 4). The stack consists of three levels made of carbon sandwich plates to reduce weight. The lowest level carries the battery with the battery management system to keep a low center of mass.
We chose a 12 cell lithium-polymer battery with a nominal voltage of 48 V and a mass of 1.5 kg. On the second level, the motor controllers are centrally attached to a ventilation shaft used for active cooling of the electric components. This level also carries the on-board computer, a fitPC IPC3 with an Intel i7 processor. On the top level, the DC/DC converter, which supplies the logic part of the electronic system is located. On the back of the third level, an Inertial Measurement Unit (IMU, VectorNav VN100) is mounted.

D. Control and Simulation framework

The on-board control framework uses the Robot Operating System (ROS). It consists of a state estimator, a high-level controller, and a low-level controller as shown in Fig. 5. The state estimator receives motor and encoder data from the low-level controller through shared memory, and from the IMU through ROS messages respectively, to estimate the robot state relative to a locally attached frame. This information is processed by the high-level controller together with high-level user inputs (such as forward velocity or type of gait) to compute the desired torque for each actuated joint. The low-level controller communicates with the eight motor controllers through an EtherCAT network. If the robot is operated in simulation mode, the high-level controller and the state estimator exchange data directly with the simulation environment through shared memory without an additional low-level controller in the loop. This setup allows using the same control and state estimation code in simulation and hardware experiments. The code can be tested thoroughly in simulation before it is used on the robot, which increases safety.

E. Simulation Setup

All simulations were run in Gazebo using the ODE physics engine. We used the stock parameters for a rigid ground plane model and did not simulate compliant ground or inclinations.

III. LOCOMOTION CONTROL

To prove the locomotion capacity of SpaceBok, simple control approaches have been implemented. The locomotion controller enables the robot to robustly execute a variety of different gaits that can be selected depending on the environment. We implemented two different control strategies. The first control strategy relies on a virtual model based controller (VMC) [13] to execute pronking (Sec. III-A) and different walking gaits (Sec. III-B). Section III-C details the optimization problem used to map the virtual forces and torques (wrench) calculated by the VMC to feet forces. The second control strategy uses a controller solely based on tracking handcrafted end-effector trajectories (Sec. III-D).

A. Pronking

During the pronking gait, two different control modes are employed depending on whether the robot has ground contact or not. During the flight phase, a simple position controller of the feet is active.

During stance, a virtual model controller is used. This controller calculates desired virtual forces and torques that should act on the center of gravity of the robot. In the following, $x$ denotes the forward direction of the robot, $y$ the sideways direction to the left and the $z$-axis points upwards. The virtual force in $x$-direction $f_x$ is calculated with a P controller based on the velocity error. The force in $z$-direction $f_z$ is calculated according to a virtual spring model which leads to the jumping motion of the gait. To compensate friction losses, the respective spring constant $k_{p,z,f}$ is higher during the acceleration phase than during the deceleration phase. Since the robot does not have an abduction DOF, forces in $y$-direction are omitted. The virtual torques $m$ are calculated based on the orientation error $e_o$. The total virtual wrench is given by

$$f_x = k_{p,x,f}(v_x^* - v_x)$$
$$f_z = k_{p,z,f}(r_z^* - r_z) + m \cdot g$$
$$m = k_p^o \cdot e_o - k_d^o \cdot \omega.$$ (3)
Fig. 6. The locomotion controller consists of three major elements, the leg coordinator, the swing leg part and the torso part. The latter are again divided into a motion generation and a motion control part.

In this formulation, the orientation error

\[ e_o = p^* \otimes p = \log(p^* \otimes p^{-1}) \]  

(4)

is provided by the IMU in form of unit quaternions. \( p \) denotes the quaternion that expresses the rotation between the inertial- and the robot frame. We use the boxminus operator as defined in [14]. The calculated virtual wrench is mapped to feet forces (Sec. III-C) which are then transformed to motor torques.

**B. Walking gaits**

Additional gaits, namely a static walk, a walking trot, and a dynamic diagonal walk have been implemented using the VMC. The difference for these gaits is that swing and stance legs have to be treated differently according to the gait pattern. The walking gait controller consists of three main parts as visualized in Fig. 6. The leg coordinator reads in the gait pattern and assigns swing and stance legs accordingly. The swing leg motion generator calculates the desired swing leg trajectory based on the current gait pattern and the desired forward velocity. In the swing leg motion controller, a controller of the form

\[ \tau_{i,j} = k_p \cdot (\varphi_{i,j}^* - \varphi_{i,j}) + k_d \cdot (\dot{\varphi}_{i,j}^* - \dot{\varphi}_{i,j}) \]  

(5)

is used to track the desired trajectory of the swing legs. The proportional and derivative gains of the controller are represented by \( k_p \) and \( k_d \). Joint angles and velocities are denoted by \( \varphi_{i,j} \) and \( \dot{\varphi}_{i,j} \), while their desired values are expressed as \( \varphi_{i,j}^* \) and \( \dot{\varphi}_{i,j}^* \).

The desired torso motion is derived from the leg motions. The desired orientation of the torso is kept constant throughout the gait pattern (zero roll- and pitch angle). The yaw angle is not controlled, which means that we do not apply a virtual torque in this direction. The desired torso height is also fixed. The torso motion along the x-axis is calculated using the weighted sum of the foot positions

\[ \rho(r_B)^* = \frac{\sum_{i=1}^{4} w_i(\phi) \cdot \rho(r_i)}{\sum_{i=1}^{4} w_i(\phi)}. \]  

(6)

The weights \( w_i \) vary depending on whether the leg is in ground contact or not (Fig. 7). This approach couples the torso motion to the motion of the feet, allowing the motion generator to work with various gait patterns.

To track the torso motion, the same VMC as introduced in Sec. III-A is used, with the difference that the desired position and velocity are tracked in both the horizontal and vertical direction:

\[ f_x = k_{p,x} \cdot (r_{x}^* - r_x) + k_{d,x} \cdot (v_x^* - v_x) \]  

(7)

\[ f_z = k_{p,z} \cdot (r_{z}^* - r_z) - k_{d,z} \cdot v_z + m \cdot g \]  

(8)

\[ m = k_p^o \cdot e_o - k_d \cdot \omega. \]  

(9)

**C. Virtual wrench mapping**

The virtual wrench is mapped to foot forces by solving a constrained quadratic optimization problem. The formulation of the problem with \( m \) feet in ground contact is:

\[ \min_x \quad ||(M x - w)||^2 \]  

(10)

s. t. \( F_{i}^n \geq F_{min} \)  

(11)

\[ -\mu F_{i}^n \leq F_{i} \leq \mu F_{i}^n \]  

(12)

\[ -\tau_{max} \leq J^T x \leq \tau_{max}, \]  

(13)

where

\[ w = \begin{bmatrix} f_x \\ f_z \\ m \end{bmatrix} \in \mathbb{R}^5: \text{virtual wrench at the center of mass} \]

\[ x = \begin{bmatrix} F_1 \\ F_2 \\ \vdots \\ F_m \end{bmatrix} \in \mathbb{R}^{2m}: \text{2D contact forces of the feet} \]

\[ M = \begin{bmatrix} I_2 & I_2 & \cdots & I_2 \\ \rho(r_1) & \rho(r_2) & \cdots & \rho(r_m) \end{bmatrix}: \text{transformation matrix} \]

\( F^n \): normal contact force

\( F^t \): tangential contact force

\( \tau \): stacked motor torques

\( J \): stacked actuator Jacobian
Due to the planar leg setup without abduction/adduction DOF, we only consider a 2-dimensional contact force.

The constraints (11) and (12) ensure desirable minimal normal forces to prevent the stance feet from losing ground contact, and limited tangential forces to prevent the feet from slipping. The torque saturation of the actuator is taken into account in (13).

In the last step, those feet forces are mapped to motor torques using Jacobian transposed mapping \( \tau = J^T x \).

**D. Foot Trajectory Controller**

The gaits implemented using the VMC approach allow for robust locomotion but cannot be used for turning. Since the legs of the system lack abduction and adduction, slippage is necessary in order to turn. However, slippage is prevented by constraint (12) in Sec. III-C. To overcome this and enable turning, we generate foot trajectories for a trotting gait, whereby each trajectory has been designed using a 9th order Bezier curve as depicted in Fig. 8. To vary the speed or enforce turning, the curve can be stretched individually for every foot by scaling the x-component of the control points.

**IV. RESULTS**

For all the experiments, the control parameters were tuned for stability and not for efficiency or maximum speed. The gains used in simulation differ from the ones used in hardware experiments. However, within the simulation, the same control parameters were used for the gravitational setting of Earth, the moon and Mars.

**A. Experimental Results**

1) **Locomotion without springs:** Tests were performed indoors and outdoors over flat ground and small obstacles.\(^1\) For these tests, no parallel elastic elements were used in the legs. For safety reasons, the robot was connected to an external power source during these tests.

With the pronking gait, SpaceBok reaches a jump height of approximately 150 mm above ground with stretched legs. The robot can jump continuously on flat terrain (Fig 10). Small errors that arise in the torso orientation during the flight phase are successfully corrected during stance. Video analysis and state estimation show a velocity of approximately 0.15 m/s.

\(^1\)https://www.youtube.com/watch?v=VmhEB7hr0ik

Using a static gait, SpaceBok can walk with up to 0.3 m/s. Thanks to the static stability of the gait, it is comparatively robust. SpaceBok can overcome an unperceived obstacle of 80 mm (50 mm plate height with additional 30 mm laths) which corresponds to 16 % of the leg length (Fig. 9). Neither visual perception nor terrain inclination estimation based on the foot positions were used in this experiment.

With the walking trot (Fig 10), the robot reaches a velocity of up to 1 m/s. A high step frequency had to be chosen to ensure the stability of the torso since the concept presented in Sec. III-B does not guarantee stability at all times. This leads to a faster desired motion of the swing legs and thus to higher errors in the reference tracking of the swing legs. Consequently, the impacts on the ground are harder than during the static gait. As a result, the robot slips at high velocities.

To allow for a dynamic walking gait with a higher stride duration, a dynamic diagonal sequence walk was implemented (Fig. 10). This gait allows velocities of up to 0.6 m/s, while impact forces and slipping are significantly reduced compared to the walking trot. In this gait, the main body is barely moving (Fig. 11).

2) **Maximum jump height test with parallel elasticity:** Single jump experiments with attached springs were conducted in a test setup with a safety crane.
In this configuration, SpaceBok reached a ground clearance of 600 mm with full leg extension. The center of mass reached a height of approx. 1.05 m.

For the robot to be able to jump continuously with springs, flight phase control of the pitch angle would be necessary. Furthermore, the estimation of spring forces was not accurate enough to allow sufficient contact force control. These issues will be tackled in future work.

B. Simulation Results

1) Simulation without springs: For the simulation of the walking gaits the springs were omitted due to their deteriorating effect on efficiency when using these gaits. The robot’s performance in low gravity was evaluated using the ROS Gazebo simulation. On flat terrain with Earth and Mars \( (g_{\text{earth}} = 9.81 \text{ m/s}^2, g_{\text{mars}} = 3.711 \text{ m/s}^2) \) increasing reference velocities were commanded. Once the robot entered a steady state, the mechanical power consumption and the actual velocity of the robot were recorded. To measure the locomotion efficiency of the robot, the cost of transport (COT) was calculated as described in [11]. The results are shown in Fig. 12. On both Earth and Mars the static gait is most efficient at slow velocities. As the velocity increases, the dynamic diagonal walking gait surpasses the static gait in terms of efficiency. At high velocities, the trot is the gait of choice. The transitions to a more efficient gait at increasing velocities occur earlier on Mars.

2) Simulation with springs: The pronking gait has been simulated on the moon with the springs attached. Velocity and efficiency of the pronking gait are significantly inferior in a terrestrial environment compared to the walking gaits. However, the gait becomes more relevant in a low gravity environment. SpaceBok reaches a velocity of 1.1 m/s with a cost of transport of 0.97 as shown in Fig. 13.

V. CONCLUSION AND FUTURE WORK

First successful walking and pronking experiments proved that SpaceBok is suited to explore dynamic gaits. The robot is able to walk statically and dynamically and pronk continuously in a terrestrial environment. The simulation indicated that the same functionality is given for low gravity environments.

The low gravity simulation unveiled that a dynamically moving robot such as SpaceBok has the potential to move fast and efficient on celestial bodies. Furthermore, pronking proves to be a valid solution for locomotion in low gravity, in particular with a mechanical design that incorporates a parallel elastic element.

In future work, physical tests in a simulated low gravity environment will be conducted at the European Space Research and Technology Centre (ESTEC). These tests aim at exploring the functionality of the physical system in low gravity as well as measuring the power consumption of the system. Furthermore, more advanced control methods will be implemented to improve the locomotion performance, in particular when moving on non-flat ground, which will allow field tests in a rough, mars-like environment.

APPENDIX

ACKNOWLEDGMENT

This project was conducted as a self-funded student project. We would like to thank all the sponsors involved in the project. Our gold sponsors NOVAGEAR, KMF, Feusi, Swiss Space Center and Aurora Swiss Aerospace, our silver sponsors Helbling, Elmo Motion Control, T-Motor, Suter Kunststoffe AG, CNC Dynamix, and our bronze sponsors RLS, Durovis, Hasler, 3D Model, Schaeffler, lib, Gysin, Distrelec, Feintool, Almatech, Klebwerkstatt Inderkum, Huber+Suhner and VectorNav.
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